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# Analysis of the Informativity of the Earth's Magnetic Field in Near-Earth Space

**Yu. A. Kopytenko**[a], **A. A. Petrova**[a, *], **I. S. Guriev**[b], **P. V. Labetsky**[b], **and O. V. Latysheva**[a]

[a] *St. Petersburg Branch of the Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, Russian Academy of Sciences, St. Petersburg, 199034 Russia*

[b] *Mozhaysky Military Space Academy, St. Petersburg, 197082 Russia*

**e-mail: aa_petrova@inbox.ru*

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**Abstract**—This paper presents the results of a study of the informativity of the anomalies of the modulus and components of the Earth's magnetic field in near-Earth space in the altitude range from 300 to 800 km. Magnetic anomalies are calculated according to a three-dimensional component model of the Earth's magnetic field of the St. Petersburg Branch of the Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation. For comparison with the empirical data obtained by the *CHAMP* and *Swarm* satellites, the magnetic anomalies and their gradients were calculated according to the component model for altitudes of 400 and 450 km. To reveal the structural features of the lithosphere of magnetoactive zones observed in near-Earth space, deep sections were constructed based on magnetic anomalies, gravity anomalies, and seismological data. The results of the study of magnetic anomalies in near-Earth space are of scientific, practical, and applied importance for solving exploratory geological and geophysical problems and issues of spacecraft navigation.

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## INTRODUCTION

The object of the study is the magnetic anomalies of the lithosphere observed by the *CHAMP* and *Swarm* spacecraft, as well as magnetic anomalies calculated at the altitudes of near-Earth space according to a three-dimensional component model [1–3].

The component model of the Earth's magnetic field (EMF) was constructed using materials of vector surveys and values calculated from modular measurements of EMF near its surface. The estimates of the error of the component model were obtained by comparing the values calculated according to the model with the vector data of aeromagnetic surveys in Scandinavia, world network of geomagnetic observatories, and measurements on the *CHAMP* spacecraft [2].

The goal of this study is to investigate the informativity of magnetic anomalies of the lithosphere in near-Earth space and the degree of their variation with altitude in the range from 300 to 800 km. Based on the interpretation of EMF anomalies [1–4, 7], gravity [8], and seismological data (http://www.isc.ac.uk), an analysis of the deep structure of the lithosphere of magnetoactive zones revealed by the spacecraft in near-Earth space was carried out. As a result of the analysis, deep sections were constructed based on magnetic anomalies, gravity anomalies, and seismological data. In the process of studying the magnetic, density, and velocity properties of the magnetic zones of the lithosphere, the location, magnetization, thickness, and density properties of the layers of the lithosphere creating magnetoactive zones were determined. The study showed that, most often, these zones tend towards the most ancient stable regions of the continental Earth's crust. Earthquake foci emphasize the contact boundaries of lithospheric inhomogeneities, fixing the direction of displacement of blocks, compression and extension axes in deep sections.

## STATEMENT OF THE RESEARCH PROBLEM

The main objective of this study is to estimate the informativity of the near-Earth space EMF based on the study of the properties of the modulus and magnetic field component anomalies. The EMF measurements carried out on the *CHAMP* and *Swarm* spacecraft make it possible to compare the anomalies calculated according to the three-dimensional component model with the experimental data recorded by the spacecraft at altitudes of 400 and 450 km, respectively.

Comparison of the modulus and vertical component anomalies observed by the *CHAMP* spacecraft with the values calculated for an altitude of 400 km according to the component model showed good agreement between the configuration and intensity of the Earth's anomalies [9–14]. At an altitude of 400 km, the arithmetic mean difference in the EMF modulus anomalies according to the spacecraft and model data was 1.50 nT, the confidence interval was ±0.05 nT, and the standard deviation was ±6.8 nT. The amplitude of the anomalies in the modulus of the EMF vector at this altitude varies in the range of ±20 nT [2]. The global level—the main magnetic field of the IGRF model [14, 15]—is used as the reference level for the anomalies of the EMF elements in the component model.

Currently, three spacecraft of the *Swarm* system (*Alpha*, *Charlie*, *Bravo*) operate in circular near-Earth orbits at altitudes of 450 and 530 km. The project foresees a gradual descent of the spacecraft to a lower near-Earth orbit up to an altitude of 300 km [12–14]. A magnetometer measuring the vector of the magnetic field strength and a magnetometer measuring the absolute values of the scalar of the magnetic field strength are used as equipment for studying the EMF.

The results of measurements of the EMF by the *Swarm* spacecraft have been published for the polar regions of the Earth. To compare with the values observed by the *Swarm* spacecraft, the anomalies of the modulus ($F$) and vertical ($Z$) components, as well as the horizontal ($H$) component of the EMF, their vertical and horizontal gradients at altitudes of 300, 450, and 530 km were calculated according to the three-dimensional component model. Calculations were performed in polar stereographic equiangular projection.

At present, considerable attention is paid to the study of the distribution of anomalies of the EMF elements at different levels of altitudes for the entire globe [2, 4, 7, 16–22, 24]. Primary importance is devoted to the informativity of the component anomalies at the priority altitudes of the spacecraft near-Earth orbits. The *International Space Station* is located at an altitude of about 400 km. The *Swarm* spacecraft operate in an altitude range of 450–530 km above the Earth's surface. For spacecraft requiring a stable power supply, Solar-synchronous orbits with an altitude of about 800 km and circumpolar inclination are used. Determination of the priority informative corridors of operating altitudes is of fundamental importance for aerospace navigation using three-component magnetometers on the spacecraft.

In order to estimate variations in the intensity of the anomalies of the modulus and $Z$- and $H$-components of the EMF with altitude, calculations of the fields for the Earth from the ocean level to altitudes of 300, 400, 450, and 530 km were carried out. This made it possible to verify the component model based on independent observed measurements on the *CHAMP* and *Swarm* spacecraft.

## ESTIMATION OF THE INFORMATIVITY OF MAGNETIC ANOMALIES IN NEAR-EARTH SPACE

To estimate the efficiency and informativity of the geomagnetic field in near-Earth space, when solving space navigation and geological and geophysical problems, the spectral characteristics and intensity of anomalies of the modulus ($F$), vertical ($Z$), horizontal ($H$), northern ($X$), and eastern ($Y$) EMF components, as well as the values of their gradients are most essential. The amplitude of the components of magnetic anomalies measured by the spacecraft within the priority corridors should exceed the level of measurement error by more than two times.

In some cases, when solving geological and geophysical problems and spacecraft navigation, small values of the above gradients measured by magnetometric functions are observed, which gives an idea of the low level of informativity of the EMF parameters. In addition, this circumstance indicates the difficulty of using statistical estimation methods for navigational support of a given accuracy of the spacecraft motion [5, 6].

One of the main factors that have a positive effect on the efficiency of solving the problems considered in the paper is the creation of high-precision on-board magnetometers. The following types of magnetometers have found wide application in outer space: ferrosonde, quantum and superconducting (SQUID). These magnetometers have a fairly high accuracy, which is characterized by errors ranging from $10^{-1}$ to $10^{-5}$ nT. This accuracy of onboard magnetometric means allows one to solve the problem of navigation support in the considered altitude range with errors in determining the spacecraft orientation and coordinates less than one angular minute and several tens of meters, respectively [4, 6].

The *CHAMP* spacecraft measured the anomalies of the $F$ and $Z$-components of EMF in near-Earth space at an altitude of 400 km. Based on these data, maps of the anomalies of the $F$ and $Z$-components of EMF for the entire globe were constructed [10, 11]. The $Z$-component model MF7 is still used as a reference [12, 13]. Thanks to this unique information, an idea was obtained about the nature of the magnetization of rocks in the lower lithosphere.

According to the MF7 model, the intensity of anomalies of the modulus and $Z$-component of EMF at an altitude of 400 km in the regions of the ancient Precambrian platforms of North America, Greenland, Eastern Europe, Siberia, Central Asia, Africa, Australia, Antarctica, as well as in the Arctic basin (Alfa and Mendeleev ridges) exceeds the level of the instrumental error in measuring EMF by more than 5–10 times.

Using measurements of the *CHAMP* spacecraft, the most magnetic zones of the Earth have been revealed by the positive anomalies of the modulus at an altitude of 400 km. In the process of the study, the authors investigated the identified zones by the anomalies of the $F$, $Z$- and $H$-components of EMF calculated on the basis of the component model (Figs. 1–3) [7]. A comparison of the $F$ and $Z$-component anomalies observed by the *CHAMP* spacecraft with the calculated values at an altitude of 400 km showed good

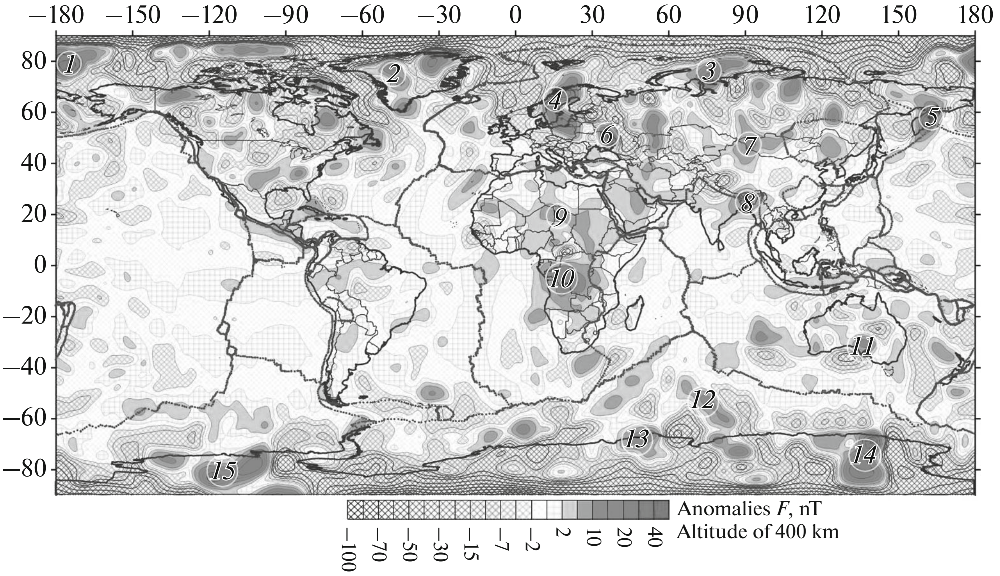

**Fig. 1.** Magnetic anomalies of the EMF modulus of magnetoactive zones at an altitude of 400 km calculated using the component model [1–3]. (*1*) Mendeleev Ridge, (*2*) Greenland, (*3*) Kara Sea, (*4*) Baltic shield, (*5*) Kamchatka Peninsula, (*6*) Voronezh massif, (*7*) Tarim Basin (Tibet), (*8*) Indian shield, (*9*, *10*) African Plate, (*11*) Australian Shield, (*12*) Kerguelen Plateau (Indian Ocean), (*13*) Enderby Land (East Antarctica), (*14*) Wilkes Land (East Antarctica), and (*15*) Mary Byrd Land (West Antarctica).

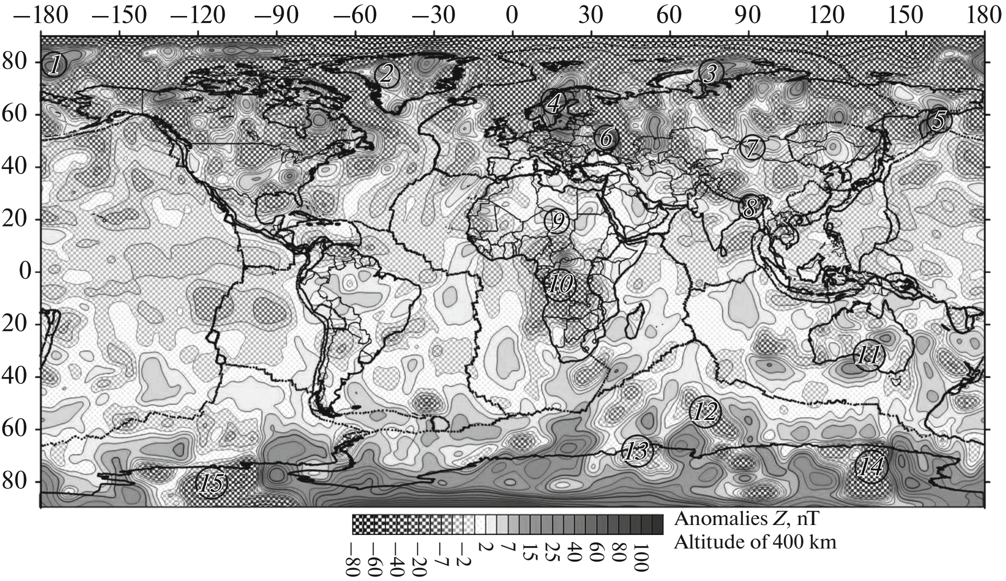

**Fig. 2.** Magnetic anomalies of the *Z*-component of the EMF at an altitude of 400 km calculated using the component model [1–3].

agreement. As a result of the analysis, 15 large magnetoactive zones were identified around the globe, which are traced in near-Earth space up to an altitude of 400 km or more (Figs. 1, 2).

The altitude calculations of the anomalies of the *F*, *H*-, and *Z*-components were performed using the EMF component model [1–3]. Maps of anomalies of the elements of terrestrial magnetism in near-Earth space have been constructed for the entire globe at altitudes of 300, 400, 500, and 800 km. They made it possible to trace variations in the intensity of anomalies in large magnetic zones due to the increased magnetization of sources of lithospheric anomalies (Table 1).

For altitudes of 300–800 km, according to the component model, the authors estimated the navigation landmarks in the form of anomalies exceeding the level of measurement error on the spacecraft in the priority high-altitude corridors of near-Earth space [4, 7]. Investigation of variations in the intensity of anomalies of the modulus and EMF components of

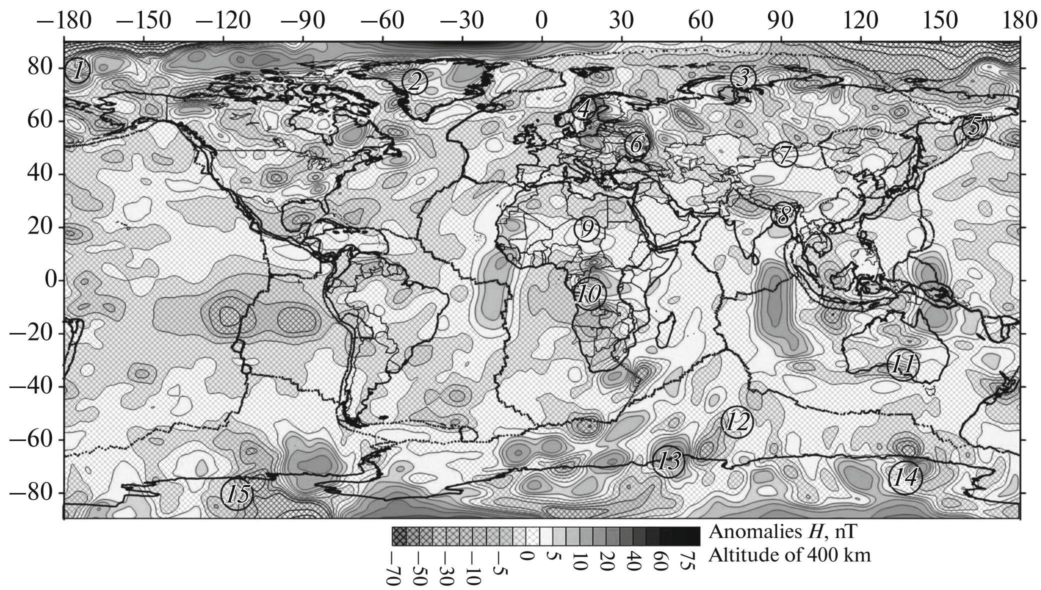

**Fig. 3.** Magnetic anomalies of the *H*-component of the EMF at an altitude of 400 km calculated using the component model [1–3].

magnetoactive zones with altitude has shown that they are quite informative and can be used in magnetic aerospace navigation up to altitudes of 400–450 km and more. However, at altitudes of ~600–800 km, 8 of 15 magnetic zones remain. Magnetic zones with nos. 1, 3, 4, 8, 10, 11, 13, and 14 are confidently distinguished by the anomalies of the *F*, *Z*-, and *H*-components. Zones with nos. 12 and 15 are traced by the anomalies of *F* and *Z*-component (Table 1).

Estimation of gradients of geomagnetic field anomalies is of fundamental importance for solving problems of aerospace magnetic navigation [6, 23]. In this study, using the component model, we calculated the vertical and horizontal gradients of the anomalies of the EMF *Z*-component for an altitude interval of 300–600 km.

The expected values of the vertical gradient of the EMF *Z*-component according to the *Swarm* measurements are 0.1–0.4 nT/km in the magnetic zones of

**Table 1.** Variations in the intensity of the *F*, *Z*-, and *H*-component anomalies of the EMF of magnetoactive zones (Figs. 1–3) with altitude in near-Earth space

| No. of anomaly | Amplitude, nT | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | altitude of 300 km | | | altitude of 400 km | | | altitude of 600 km | | | altitude of 800 km | | |
| | *F* | *Z* | *H* | *F* | *Z* | *H* | *F* | *Z* | *H* | *F* | *Z* | *H* |
| 1 | 50 | 50 | 15 | 30 | 30 | 10 | 13 | 12 | 2 | 4 | 1 | 1 |
| 2 | 25 | 20 | 12 | 10 | 10 | 7 | 2 | 1 | 3 | 0 | 0 | 0 |
| 3 | 30 | 25 | 13 | 15 | 15 | 10 | 6 | 5 | 3 | 0.5 | 0 | 1 |
| 4 | 30 | 30 | 15 | 20 | 20 | 10 | 10 | 7 | 2 | 4 | 1 | 1 |
| 5 | 40 | 40 | 12 | 20 | 20 | 7 | 7 | 7 | 3 | 3 | 2 | 1 |
| 6 | 60 | 60 | 10 | 30 | 30 | 4 | 7 | 7 | 0 | 2 | 0 | 0 |
| 7 | 15 | 15 | 8 | 10 | 10 | 5 | 5 | 3 | 2 | 2 | 0 | 1 |
| 8 | 15 | 15 | 7 | 10 | 10 | 5 | 6 | 5 | 4 | 3 | 1 | 2 |
| 9 | 10 | 7 | 6 | 6 | 5 | 4 | 4 | 2 | 2 | 3 | 0 | 1 |
| 10 | 25 | −25 | 12 | 15 | −15 | 7 | 10 | −10 | 4 | 7 | −7 | 3 |
| 11 | 15 | −15 | 10 | 10 | −10 | 5 | 4 | −2 | 3 | 0.5 | 1 | 0 |
| 12 | 15 | −15 | 5 | 10 | −8 | 2 | 6 | −3 | 1 | 1.5 | 2 | 1 |
| 13 | 20 | −15 | 25 | 10 | −8 | 15 | 6 | 0 | 10 | 1.5 | 5 | 7 |
| 14 | 30 | −30 | 20 | 20 | −20 | 10 | 10 | −12 | 5 | 6 | −5 | 4 |
| 15 | 30 | −30 | 0.5 | 20 | −20 | 0 | 10 | −12 | 0 | 7 | −7 | 0 |

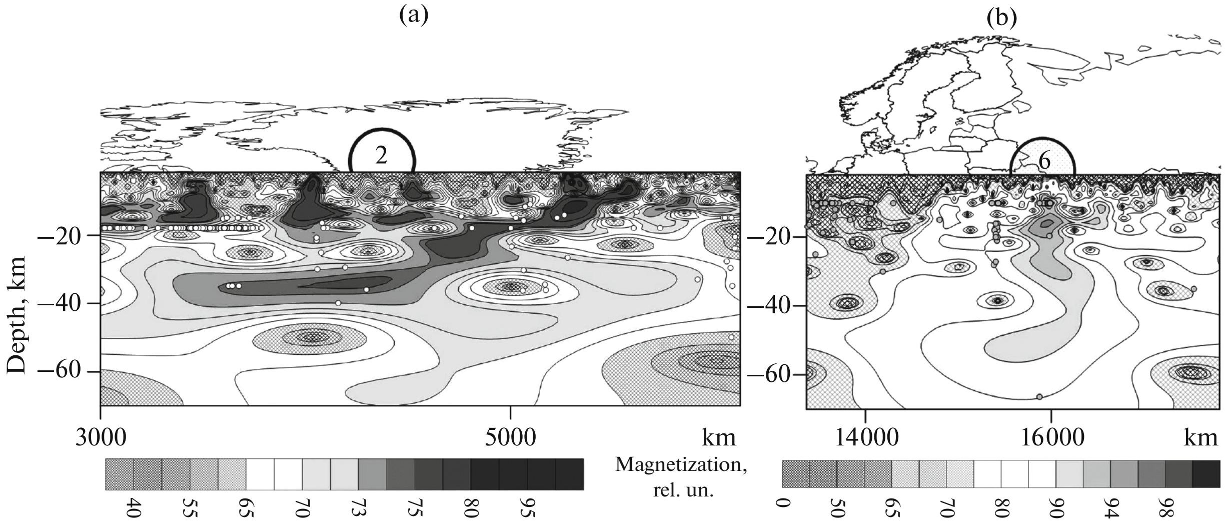

**Fig. 4.** Magnetic sections through zones (a) no. 2 (Greenland) and (b) no. 6 (Voronezh massif of the East European platform).

Eastern Europe at an altitude of 300 km and 0.1–0.15 nT/km in the zones of North America, Greenland, and the Arctic Basin. At a spacecraft flight altitude of 450 km, the vertical gradient is 0.02–0.1 nT/km in Eastern Europe, while it is 0.02–0.06 nT/km in North America, Greenland, and the Arctic Basin. At a spacecraft flight altitude of 530 km, the vertical gradient of the $Z$-component can have values of 0.02–0.08 nT/km in Eastern Europe and 0.02–0.04 nT/km in North America, Greenland, and the Arctic Basin.

The expected values of the horizontal gradient of the EMF $Z$-component according to measurements of the *Swarm* spacecraft at an altitude of 300 km can be 0.01–0.3 nT/km in Eastern Europe, and 0.01–0.1 nT/km in the North America, Greenland, and Arctic Basin. At an altitude of 450 km, the horizontal gradient of the $Z$-component is 0.04–0.1 nT/km in Eastern Europe and 0.01–0.04 nT/km in the North America, Greenland, and Arctic Basin. At an altitude of 530 km, the horizontal gradient can have values of 0.03–0.06 nT/km in Eastern Europe and 0.01–0.03 nT/km in North America, Greenland, and the Arctic Basin.

The anomalies of the $H$- and $Z$-components of the EMF in near-Earth space are of interest for studying the nature of the rocks magnetization in the lower lithosphere. Anomaly components enhance the ability to quantitatively interpret the magnetic field. Component anomalies make it possible to more reliably represent physical processes in the Earth's crust and upper mantle. They make it possible to study the structural features of the lower lithosphere, search for geothermal zones and ore minerals, and clarify the spatial and temporal displacements of tectonic plates [2–4, 11, 20, 24–29].

In order to estimate the thickness of the magnetoactive layers, the properties of magnetization and the density of the lithosphere rocks, profiles were drawn through the identified magnetic zones, crossing them in latitudinal directions. The deep sections were constructed using the spectral-spatial analysis (SPAN) method [25, 29] based on the EMF modulus anomalies measured near the Earth's surface, gravity anomalies, and seismological data. Earthquake foci are plotted by dots on deep sections. The results of a complex analysis of deep sections revealed the features of the magnetic and density properties of rocks in the magnetoactive zones of the lithosphere.

A deep section through magnetic zone no. 2 showed that the main sources of magnetic anomalies in the ancient shield of Greenland are located at depths of 7–10, 14–17, and 30–36 km (Figs. 1, 4a). They are confined to weakened layers with a low density, on the boundaries of which there are earthquake foci (Fig. 5a).

A deep section through magnetic zone no. 6 (Figs. 1, 4b) revealed vertical sources of magnetic anomalies in the depth range of 7–12, 13–20, and 25–37 km located in a weakened fault zone of low density, in which earthquake foci were recorded in the range from 10 to 66 km at the boundaries of blocks of different densities (Fig. 5b). Comparison of the density section with the depths of the earthquake foci near the line of the profile showed that the location of the foci is consistent with the obtained picture of the distribution of density formations. Earthquake hypocenters tend towards the contacts of rocks of different densities on the top and bottom and at the lateral boundaries of density and magnetic heterogeneities of horizons and blocks (Fig. 5).

EMF component anomalies contain significantly more information about the magnetic properties of rocks of the Earth's crust than do modulus data. This makes it possible to approach the solution of the question of the magnetization of the anomalies sources that

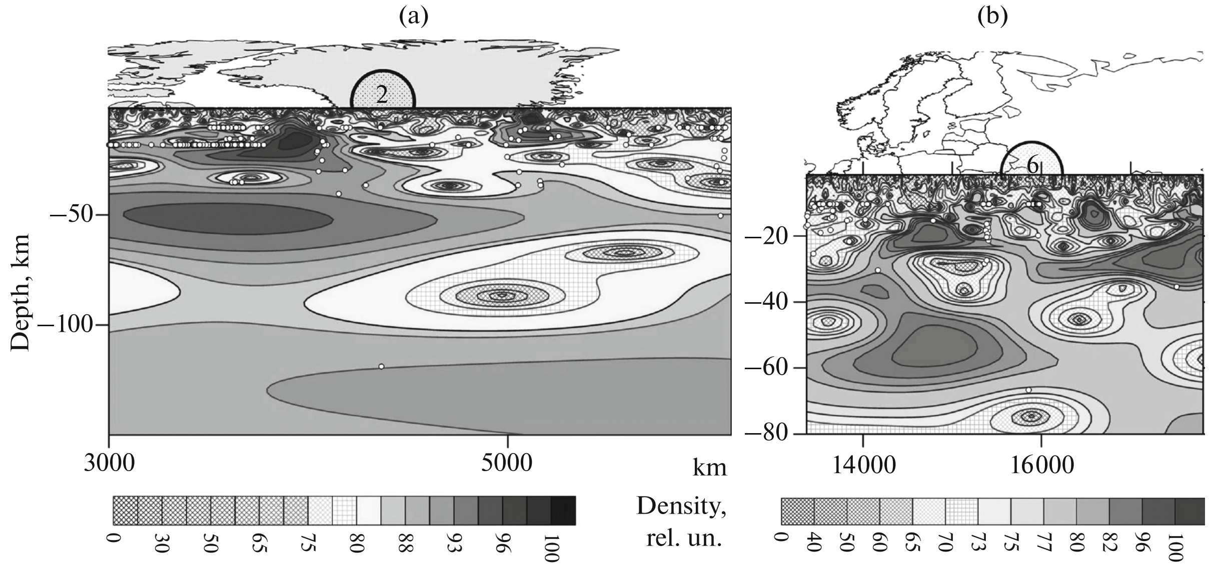

**Fig. 5.** Deep density sections through magnetically active zones (a) no. 2 (Greenland) and (b) no. 6 (Voronezh massif of the East European platform).

carry information about the current state of deep formations in the lower lithosphere, which allows to reveal ancient geoblocks, which magnetization was formed at values of the main EMF that differed from the modern one. It gives an opportunity to obtain information on the magnitude and direction of the EMF vector and to estimate the most probable time of the inversion periods.

As a result of studying the nature of variations in the component anomalies with altitude, the features of the physical state of the rocks of the “coldest” magnetized blocks of the lithosphere, located at significant depths, were revealed. Particular interest is presented by the magnetic anomalies of the $Z$- and $H$-components of ancient Precambrian lithosphere formations, which can have both inductive and thermoremanent magnetization, including those formed during periods of EMF inversions [3, 24, 25].

This phenomenon is most clearly expressed in the polar regions of the Earth near the magnetic poles. For example, in the Amerasian Basin in the Arctic (Alpha and Mendeleev Ridges) and on the Eastern Plateau of the Precambrian East Antarctic Platform, where in the last 100 years the main values of the $H$-component have been small and less than 0.1–1% of the maximum values (Fig. 3). Nevertheless, intense $H$-component anomalies were revealed here, which are traced to near-Earth altitudes of ≥400 km. Extended submeridional $H$-component anomalies that manifested themselves in the regions of the East Indian Ridge and along the Mid-Atlantic Ridge from the Sierra Leone Basin through the Romansh Fault to the Brazilian Basin are interested. These anomalies were revealed at an altitude of 400 km in the maps of the modulus and $Z$-component, but they are most clearly distinguished in the maps of the EMF $H$-component.

Great interest is presented by intense anomalies of the $H$-component near the magnetic pole in the circumpolar region of the Arctic, where the main field of the $H$-component is ≤0–500 nT. The anomalies of the $H$-component of the Alpha and Mendeleev Ridges near the Earth’s surface are ≥400 nT. Calculations using the component model for an altitude of 300 km allow anomaly values of more than 10–15 nT (Fig. 3, Table 1). Most likely, this means that the rocks of the Alpha and Mendeleev Ridges, in addition to inductive magnetization, have significant thermoremanent magnetization. It is possible that thermoremanent magnetization could have persisted since the times, when there was no magnetic pole in the Arctic or the rocks of the Alpha and Mendeleev Ridges were formed and magnetized in other latitudes, where the main values of the $H$-component have large values, such as in the equatorial region [1–3, 24].

The magnetic anomalies of the components create a clearer knowing of the nature of variations in the EMF vector during periods of inversions. The study of component anomalies gives a new impulse to the research of the space–time concept of the reconstruction of tectonic plates [3].

## MAGNETIC ANOMALIES OF THE EARTH’S POLAR REGIONS IN NEAR-EARTH SPACE

At present, the first measurement data of the *Swarm* spacecraft observed at an altitude of 450 km have been published [12–14]. For the polar regions of the Arctic and Antarctic, models of anomalies of the EMF $Z$-component at an altitude of 450 km and mod-

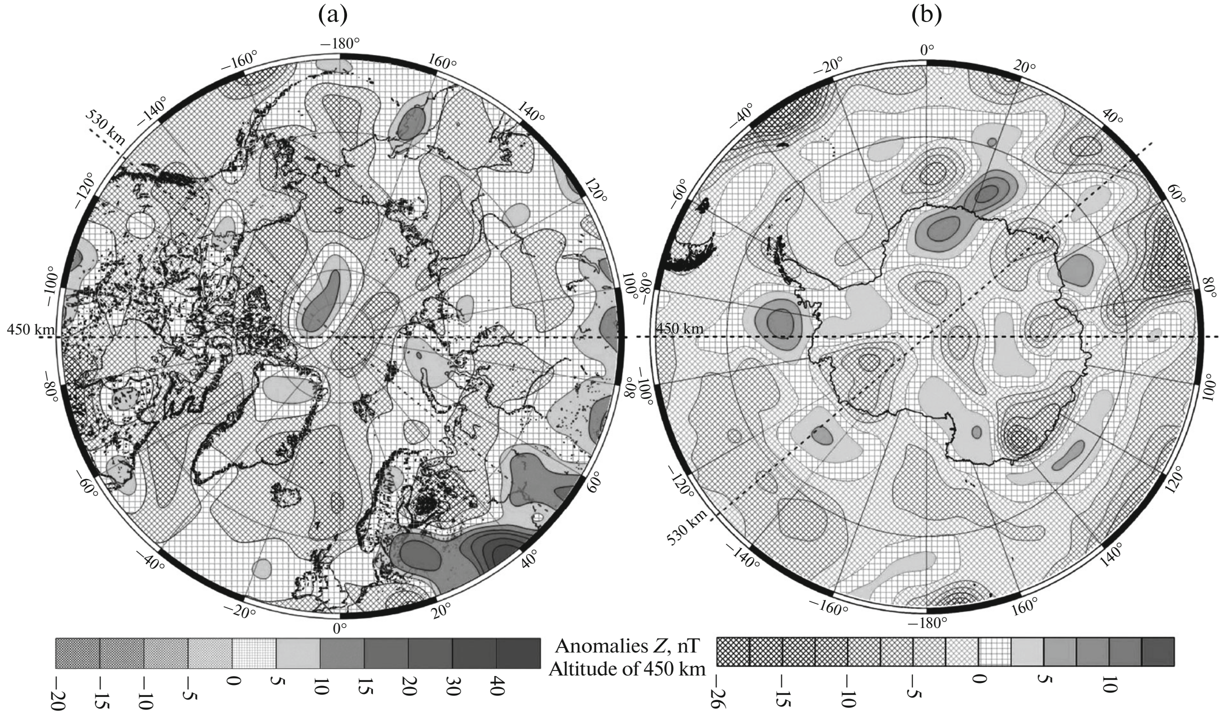

**Fig. 6.** Magnetic anomalies of the $Z$-component of EMF in (a) the Arctic and (b) the Antarctic at an altitude of 450 km calculated using the component model [1–3]. Magnetic anomalies are shown in polar stereographic equiangular projection. Dashed lines are the trajectory of the *Swarm* spacecraft orbit (ESA image) at altitudes of 450 and 530 km.

els of anomalies recalculated from the altitude of the spacecraft flight to the Earth's surface are presented.

For comparison with the high-latitude magnetic anomalies measured by the *Swarm* spacecraft in the polar regions [10], the component model was used to calculate the anomalies of the $F$, $Z$-, and $H$-components of the EMF for an altitude of 450 km (Figs. 6–8) [1–3]. Comparison of the calculated values of the $Z$-component anomalies with the observed *Swarm* spacecraft in Arctic and Antarctic showed good agreement of the component model with independent estimates of measurements on the spacecraft. The discrepancies in the polar regions of the $Z$-component anomalies are less than 2 nT.

For the Arctic region, the calculations of the expected magnetic anomalies of the $Z$- and $H$-components of the EMF at an altitude of 530 km were performed (Fig. 9). Intensity $A$ and length $L$ of anomalies $F$, $Z$, and $H$ of the EMF elements for all three expected altitudes of the *Swarm* spacecraft orbits (300, 450, and 530 km) [12–14] are given in Table 2.

The configuration and morphology of the expected vertical and horizontal gradients of the EMF modulus anomalies in the high-latitude region of the Arctic are presented for an altitude of 450 km (Fig. 10).

The *Swarm* spacecraft orbit path at an altitude of 530 km crosses one of the largest magnetoactive structures of the Arctic Ocean in the Amerasian Basin near 80° N latitude, the Alpha Ridge (AR) (Figs. 6–9). Linearly extended magnetic anomalies of the Alpha Ridge near the Earth's surface have an intensity of 500–1500 nT [30, 31]. A deep section was constructed along the *Swarm* spacecraft path based on the surface values of the $Z$-component anomalies, intersecting the magnetoactive zone of the Alpha Ridge, which manifests itself in the $Z$-component anomalies in near-Earth space [2, 4, 12–14, 24] (Fig. 11).

Analysis of the magnetic section showed that the main sources of anomalies in the magnetoactive zone of the Alpha Ridge are located at depths of 6–11 and 15–21 km. A magnetic and dense marker horizon is located at a depth of 6–11 km. The vertically magnetized layer at depth of 15–21 km is confined to a powerful vertical fault zone of low density clearly traced along the section up to 27 km and possibly extending up to 40 km (Fig. 11b).

**Table 2.** Intensity $A$ and length $L$ of anomalies $F$, $Z$, and $H$ of the EMF elements in the orbits of the *Swarm* spacecraft in the zone of the Alpha Ridge of Amerasian basin of the Arctic Ocean

| Altitude, km | Anomaly $F$ | | Anomaly $Z$ | | Anomaly $H$ | |
|---|---|---|---|---|---|---|
| | $A$, nT | $L$, km | $A$, nT | $L$, km | $A$, nT | $L$, km |
| 300 | 2.5–25 | 1260 | 2.5–22 | 1260 | 5–13 | 1800 |
| 450 | 2.5–14 | 1240 | 2.5–13 | 1237 | 5–9 | 1500 |
| 530 | 2.5–10 | 1210 | 2.5–10 | 1220 | 5–7 | 1350 |

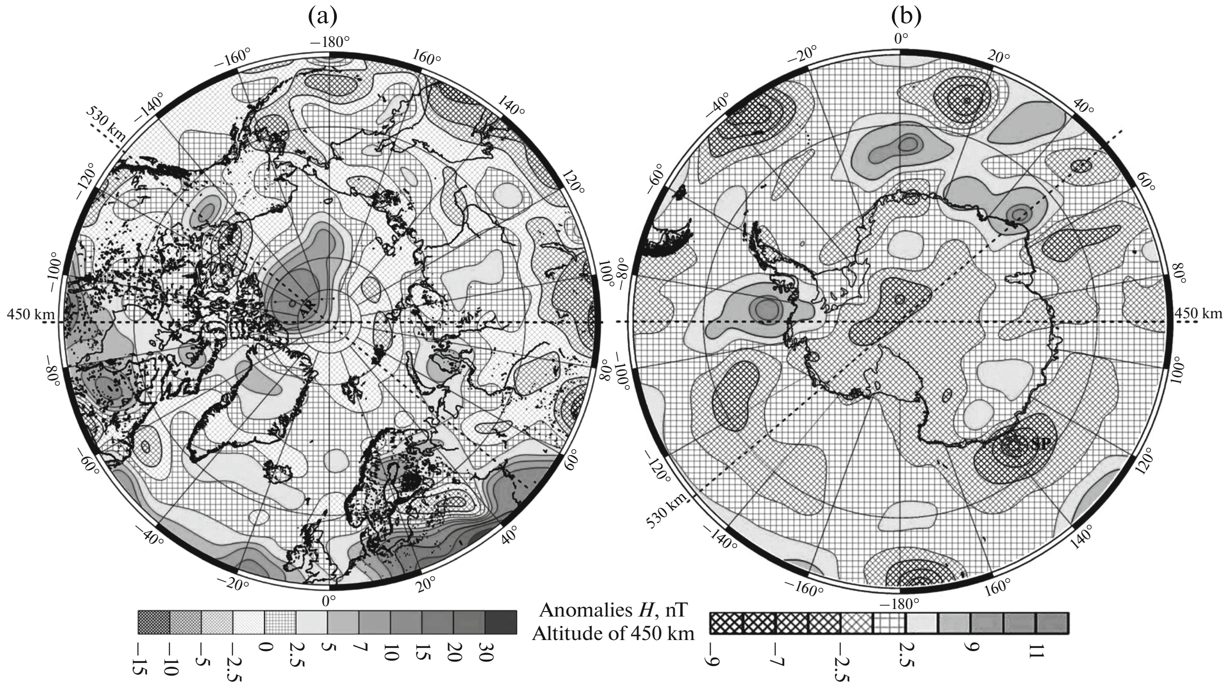

**Fig. 7.** Expected magnetic anomalies of the *H*-component of EMF in (a) the Arctic and (b) the Antarctic at an altitude of 450 km calculated using the component model [1–3]. Magnetic anomalies are shown in polar stereographic equiangular projection. Solid line with dots is displacement of the magnetic pole in the north polar cap from 1900 to 2020 [17] (a); dotted lines are *Swarm* orbits (ESA image).

The weakly magnetic layer traced at depth of 33–43 km is confined to the periphery of dense formations in the lower lithosphere underlying the ancient North American platform (Figs. 1, 11a).

*H*-component anomalies typical for the Alpha Ridge and extending to the Mendeleev Ridge Great are of big interest (Figs. 3, 7–9). Calculations showed that the main source of the *H*-component anomalies is a layer at depth of 15–20 km. The magnetoactive zone of the Alpha Ridge is located in the region of the magnetic pole (Figs. 7, 9), where the main value of the *H*-component is small (0–500 nT) [17]. These anomalies of the *H*-component are typical for the Precambrian crust of North America and Europe [7, 26]. It is possible that the Alpha Ridge also arose in the Precambrian.

Earthquake foci in deep sections are located on the boundary surfaces and contacts of layers of different density and magnetization. The results of a complex analysis of deep sections revealed the structural features of the magnetoactive zone of the lithosphere in the region of the Alpha Ridge.

## RESULTS OF STUDYING MAGNETOACTIVE ZONES IN REGIONS OF ANCIENT GEOBLOCS OF THE LITHOSPHERE

The Early Precambrian crust lies at the foundation of the continents. The occurrence of a significant part of minerals is associated with the Precambrian formations. Magnetoactive zones of Precambrian geoblocks are of particular interest for solving exploratory geological and geophysical problems. Investigation of the deep structure of ancient geoblocks makes it possible to identify areas that are promising for ore and diamondiferous minerals [25, 26, 28, 29, 32, 33].

Based on the study of deep sections passing through the geoblocks of the Precambrian crust of the continents, an estimate was made of the power of the magnetoactive layers, magnetization and density properties of the lithosphere of magnetic zones manifested in near-Earth space. The sections show schistosity zones of the Earth's crust, lateral and vertical faults, fluid systems, and migration paths of thermofluid flows.

As a result of the analysis of magnetic and density sections of the Earth's crust, the location of deep-focus fluid systems and endogenous channels of fluid-magmatic processing of ancient foundation rocks, which play a primary role in the generation of a significant part of minerals, was revealed [25, 26, 28, 29].

The magnetic and density sections of the Precambrian geoblocks of the Greenland Shield (zone no. 2), the Voronezh massif (zone no. 6) (Figs. 4, 5), the North American and East European platforms (Fig. 11) showed a two-layer structure of magnetic formations of the magnetoactive zones, observed in near-Earth space at altitudes of 400–450 km. The sources of magnetic formations are located near the base of the upper

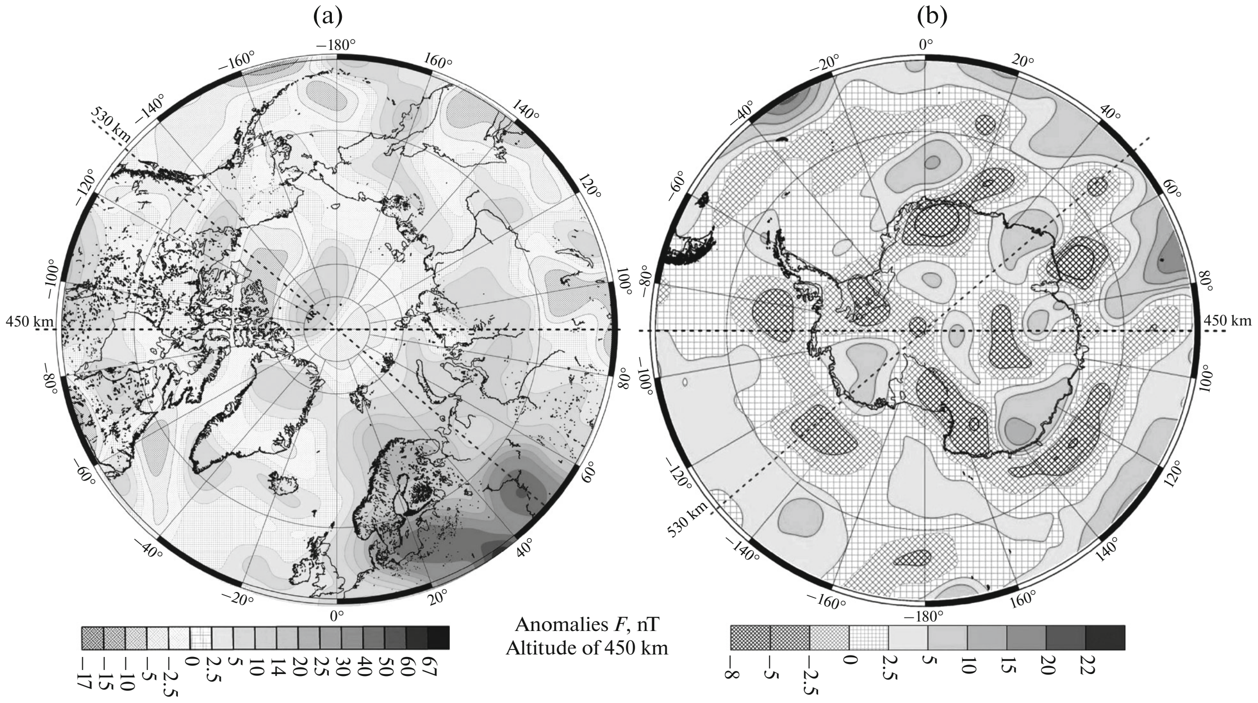

**Fig. 8.** Magnetic anomalies of the EMF modulus in (a) the Arctic and (b) the Antarctic at an altitude of 450 km calculated using the component model [1–3]. Dashed lines are the orbit trajectory of the *Swarm* spacecraft (ESA image).

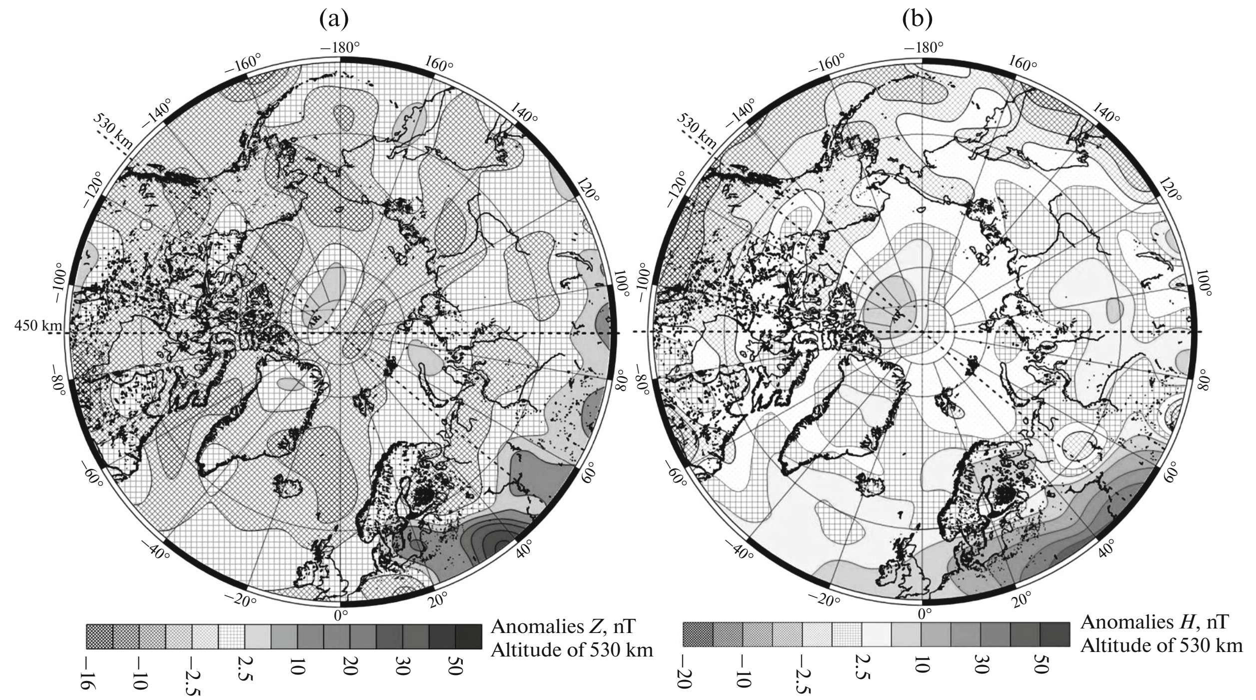

**Fig. 9.** Magnetic anomalies of the (a) vertical and (b) horizontal EMF components in the Arctic at an altitude of 530 km calculated using the component model [1–3]. Symbols are the same as in Fig. 7.

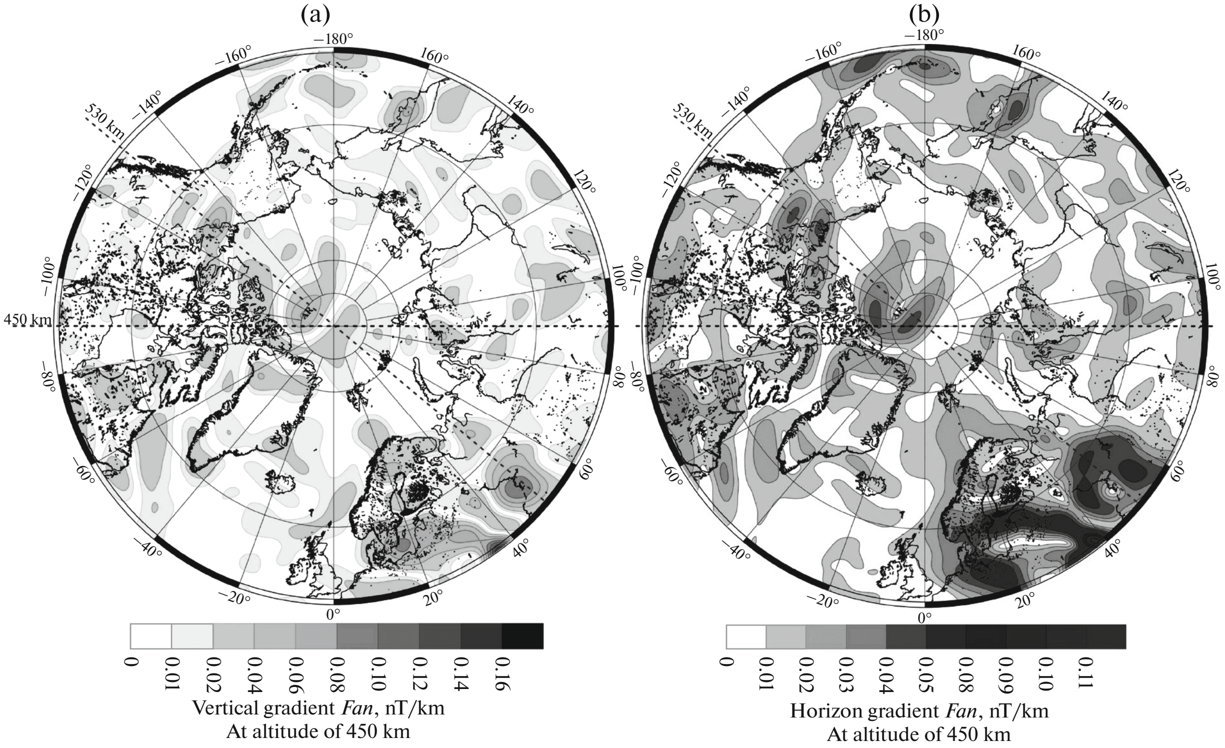

**Fig. 10.** Expected gradients of magnetic anomalies of the EMF modulus in the Arctic at an altitude of 450 km: (a) vertical and (b) horizontal calculated using the component model [1–3]. The projection is polar (stereographic equiangular).

crust and in the lower crust. Earthquake foci are confined to the boundaries of magnetic and density heterogeneities of the lithosphere.

Based on the use of a complex technology for the interpretation of geophysical data, new ideas about the layering and vertical fragmentation of the structure of the Earth's crust were obtained. An estimation of the density properties of magnetic geological formations of the lithosphere of different ages has been carried out. This made it possible to trace the paths of thermofluid flows along the fault zones of ancient blocks and to reveal lateral stratification and vertical fragmentation of the inhomogeneities of the Earth's crust and mantle using an example of magnetoactive zones of the globe traced in near-Earth space (Figs. 1, 2). The results obtained make it possible to identify hydrothermal zones, fluid-explosive diamondiferous formations, and areas of metasomatically modified rocks, promising for ore minerals [25, 26, 28, 29, 32, 33].

In the process of studying the magnetic, density, and velocity properties of the lower lithosphere, the location of the most dense and magnetic inhomogeneities was determined. The boundaries of these formations are underlined by earthquake foci, which show the direction of displacement of the lithosphere geoblocks [7].

On the basis of complex studies of ancient continents near the base of the upper crust, a magnetoactive magnetite zone has been identified. It arose as a result of the processes of regional metamorphism of the Early Precambrian during the granitization of metabasites with the replacement of femic minerals with salic ones with the release of magnetite [25, 26, 28].

Precambrian magma is characterized by a strong enrichment in iron minerals. It created magnetic horizons of magnetite zones, which can be sources of iron during the formation of deposits of jaspilites (ferruginous quartzites). Jaspilites are one of the most ancient mountain formations, dating back to the Proterozoic and Archean eras. Magnetic anomalies of the Precambrian formations are traced in near-Earth space up to an altitude of 400–450 km. The physical conditions at the bottom of the upper crust are favorable for the formation of thermoremanent and viscous magnetization. The magnetite zones of the Precambrian crust are associated with increased values of the magnetic anomalies of the *H*- and *Z*-components in near-Earth space [24, 26].

On the density, magnetic, and velocity sections of the ancient blocks of the lithosphere, dense magnetoactive layers have been revealed at the bottom of the upper and lower crust. They are clearly reflected in the EMF anomalies at near-Earth altitudes measured on the spacecraft according to the modulus and *Z*-component anomalies and calculated for all elements of the EMF component model [2, 7, 26].

In the process of analyzing the magnetoactive zones of the Precambrian geoblocks of the continents according to density sections in the lower lithosphere,

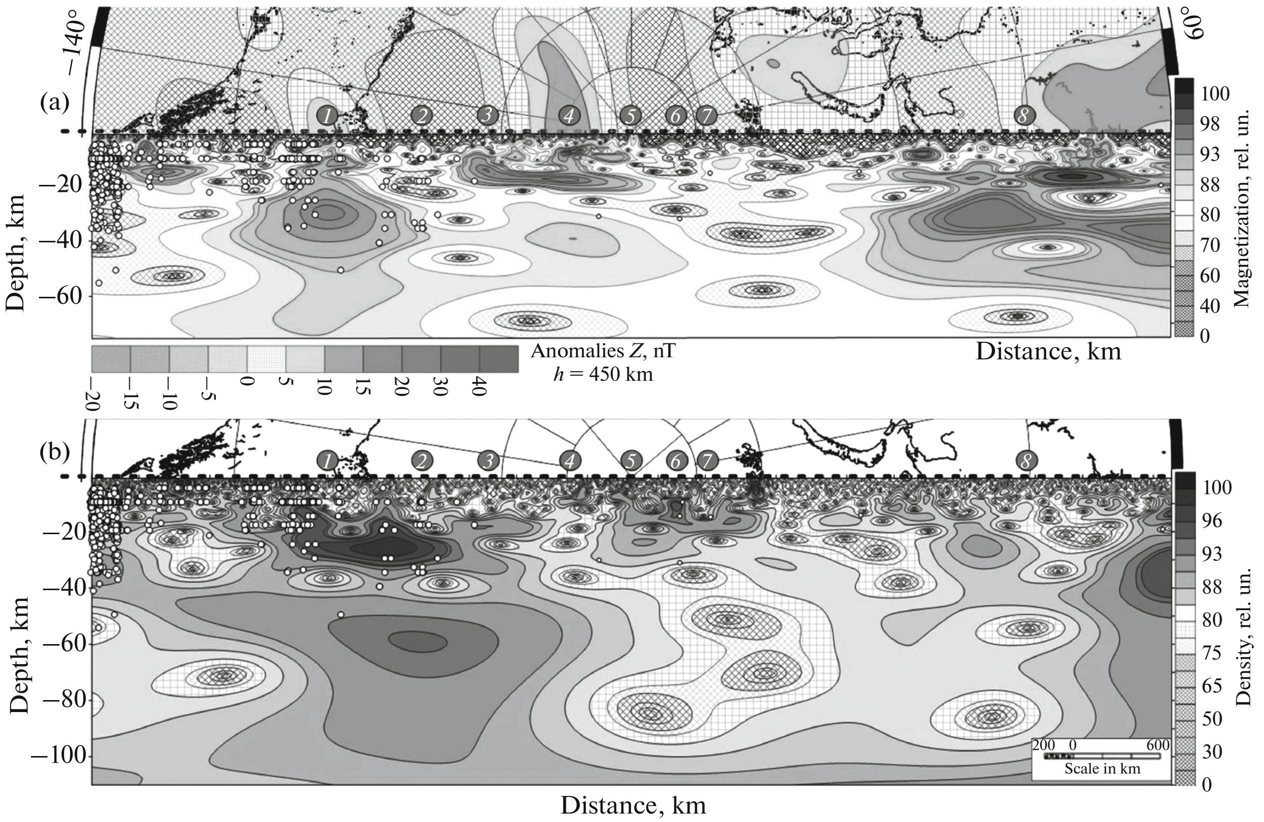

**Fig. 11.** Deep sections of the Arctic basin. (a) Magnetic and (b) density sections. The magnetic section is shown against the background of the *Z*-component anomaly map at an altitude of 450 km [1–3]. (*1*) North American platform, (*2*) Beaufort Sea, (*3*) Canadian Basin, (*4*) Alpha ridge, (*5*) Lomonosov ridge, (*6*) Gakkel ridge, (*7*) Nansen Basin, and (*8*) East European platform. White circles are earthquake foci. The dotted line is the *Swarm* orbit trace.

marking layers and horizons were identified at depths of 25–50 km. In North America, dense horizons have been identified at depth of 33–55 km. Dense layers are identified at a depth of 30–40 km in Greenland, and 38–48 km at the Baltic shield [26, 28, 30]. The thickness of the magnetized layers of the lithosphere varies from 10 to 25 km, and the intensity of the magnetic anomalies of the Precambrian blocks in near-Earth space is from 10 to 60 nT (Table 3).

The global thermal model for the continental lithosphere (TC1) constructed according to measurements of heat flow in boreholes and on the basis of electromagnetic studies, indicates the existence of Archean cratons with typical lithosphere thicknesses up to 200–250 km [34]. The TC1 model shows significant thermal heterogeneity within the continental upper mantle. The depth map of the Curie isotherm for magnetite (~550°C) gives an idea of the possible thickness of the magnetoactive layer of ancient cratons.

The study of rocks in geological sections showed that the densities and velocities of rocks are interconnected by a linear dependence on the composition of rocks and the degree of metamorphism [26]. This made it possible to establish the values of deep geophysical parameters. Analysis of the material composition of the rocks of deep sections made it possible to determine the geological and material nature of magnetite zones. Physical conditions at the bottom of the upper crust are favorable for the formation of inductive and thermoremanent magnetization. This is probably why magnetite zones of ancient geoblocks of the Earth's crust create high values of magnetic anomalies in near-Earth space (Figs. 1–3) [2, 7, 35].

The magnetization of deep rocks in the lower horizons of the Early Precambrian crust is determined mainly by the concentration of magnetite and inductive magnetization up to the Curie isotherm of magnetite. The conditions at the bottom of the continental crust can be favorable for the formation of modern viscous magnetization, which is reflected in the anomalies of the *Z*- and *H*-components of the EMF. In the regions of the Early Precambrian crust, regional magnetic anomalies are observed, which are traced up to altitudes of ≥400 km.

According to aeromagnetic and satellite survey, the average magnetization of the lower crust of the Precambrian blocks was estimated: 5 A/m for central Canada, 2 A/m for northwestern Germany, 2–4 A/m for the Ukrainian Shield, and 3.5 A/m for the United States [26]. The obtained estimates do not contradict

**Table 3.** Thickness of the magnetized layer of the lower crust and the amplitude of magnetic anomalies of Precambrian geoblocks in near-Earth space

| Name | Thickness, km | $A$, nT $h$ = 100 km | $A$, nT $h$ = 400 km | $A$, nT $h$ = 600 km |
|---|---|---|---|---|
| North America | 10 | ≥60 | ≥10 | 2.5 |
| Greenland | 10 | ≥90 | ≥10 | 2.5 |
| Baltic shield | 12 | ≥100 | ≥20 | 7–10 |
| Ukrainian shield | 15 | ≥160 | ≥18 | 7 |
| Voronezh massif | 25 | ≥170 | ≥19 | 7 |
| Eastern Siberia | 10 | ≥50 | ≥10 | 5 |
| Africa | 20 | ≥60 | ≥10 | 7 |
| Australia | 10 | ≥40 | ≥10 | 4 |
| Antarctica | 12 | ≥100 | ≥20 | 10 |

data from direct measurements of the magnetization of deep crustal rocks [36] and statistical calculations based on spacecraft measurements, which make it possible to take the average global apparent induced magnetization to be from 0.3 to 0.6 A/m, the average value of the magnetic crust thickness from 23 to 30 km, and the root-mean-square value of the field between 190 and 205 nT with a 95% probability [20].

The results of the interpretation of magnetic anomalies made it possible to reveal the structural features of different magnetoactive layers of the lithosphere [2, 7, 10, 11, 25–30]. Deep density sections, taking into account seismological data, created an idea of the distribution of density inhomogeneities and the direction of displacement of the contact surfaces of the layers of the Earth's crust. This makes it possible to clarify the internal structure of the lithosphere and to approach the solution of the question of the nature of the magnetization of the sources of regional and large regional anomalies reflecting the physical state of the oldest blocks of the continental and oceanic crust [1, 2, 10].

A complex study of the magnetic, density, and seismological characteristics of the Early Precambrian crust, which makes up the foundation of the continents, allows us to approach the estimation of its deep structure at the material level and show that regional geomagnetic anomalies reflect the influence of magnetite-containing layers existing at depths of more than 10–35 km.

Currently, geomagnetic technologies have been successfully applied to search for minerals in hard-to-reach areas of the polar zones [4, 25, 32, 33].

The deep structure of the seismic focal zones of the Kuril–Kamchatka trough, which manifests itself in the form of intense anomalies near the Earth's surface and at altitudes up to 450 km, has been studied using the magnetic anomalies of the modulus and $Z$- and $H$-components of the EMF. Magnetic anomalies of the magnetoactive zone, caused by submerging magnetized layers in the region of low mantle temperatures in the subduction zone, are clearly manifested in the anomalies of the components of the EMF induction vector in near-Earth space [2, 3].

Submerged magnetoactive geoblocks of the ancient foundation are of particular interest. Magnetic anomalies of near-Earth space have revealed a possible continuation of the foundation of the western coast of Africa into the deep-sea basins of the southern part of the Atlantic Ocean (Figs. 1–3). Magnetic anomalies in the Sierra Leone Basin and the Brazilian Basin are traced according to the measurements of the *CHAMP* spacecraft at an altitude of about 400 km. Calculations using the component model assume that anomalies of the vertical and horizontal components of EMF with an amplitude of ~4–5 nT can be detected up to an altitude of 800 km. Deep density and magnetic sections and seismological studies of these basins have revealed a dense and magnetic horizon in the lower lithosphere at a depth of 35–50 km.

As a result of a complex study of magnetic anomalies, gravity anomalies, taking into account the distribution of the depths of earthquake foci, the specificity of the internal structure of the magnetoactive zones of the lithosphere was revealed and a new idea of the distribution of lithospheric inhomogeneities in the Earth's crust and mantle was obtained. This made it possible to develop a system of prospecting geophysical criteria for predicting potentially ore-bearing areas based on the peculiarities of the influence of depth factors [2, 25, 26, 28, 29, 32, 33].

## CONCLUSIONS

In this paper, using specific examples, we demonstrated the capabilities of the EMF component model, which allows one to calculate the anomalies of the components and their gradients in near-Earth space, beginning from sea level to the altitudes of the spacecraft, which is of scientific, practical, and applied significance.

Comparison of the calculated values of the modulus and the $Z$-component with anomalies according to independent spacecraft observations at altitudes of 400–450 km confirmed that the component model constructed on the basis of surface airborne and hydromagnetic surveys is of good quality. This allows to make predictions of the expected component anomalies and their horizontal and vertical gradients for different altitudes in near-Earth space.

Deep sections of the magnetic zones of the lithosphere revealed the structural features of the Earth's crust in the ancient regions of the Earth and the specificity of the fluid-magmatic activity of the upper mantle, which opens up new possibilities for exploration of ore-generating structures of minerals and studying the geological evolution of the Earth's crust.

Based on the results of the geophysical studies of the deep structure of the Earth's crust and mantle, a refined model of the lithosphere of magnetoactive zones was obtained taking into account the peculiarities of the influence of depth factors.

The performed studies of the anomalies of the EMF components create the base for identifying variations in the geomagnetic field in the past and provide important information about the nature of the EMF generation, which makes it possible to clarify and understand the dynamic process of plate tectonics.

To solve geological, geophysical, and navigational problems, it is necessary to develop modern high-precision altitude models of the EMF based on national vector magnetometric surveys of near-Earth space using a spacecraft.

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